Extraplanar Emission-Line Gas in NGC 891

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ABSTRACT

We have used spectroscopy and high resolution imaging to study the disk-halo interaction in the edge-on spiral galaxy NGC 891, which is known to have extraplanar gas. Hα imaging of the NE side of this galaxy reveals diffuse emission-line gas both above and below the plane, as well as new bubble-like structures on 0.5 — 1 kpc scales emerging from the disk. The diffuse emission is best modeled in the radial direction as a disk of constant emission measure with a sharp cutoff. Long-slit spectroscopy of the Hα line within 2.4 kpc of the galaxy's plane shows departures from the velocity structure found in a model with strict coronation. The departures from coronation range up to 40 km s^{-1}, consistent with galactic fountain theory.

Subject headings: Galaxies: Interstellar Matter, Galaxies: Individual (NGC 891)

1. Introduction

Current theories of the interstellar medium of our galaxy postulate a strong connection between gas in the disk and gas in the halo. Galactic fountain theory, first introduced by Shapiro & Field (1976), presents a picture of hot gas escaping from the disk, cooling in the halo, and falling back onto the disk. This idea was further developed in the galactic chimney model of Norman & Ikeuchi (1989), in which the hot gas reaches the halo via "chimneys" formed by the breakout of superbubbles from the disk.

These theories were developed not only to explain phenomena in our galaxy such as high velocity HI clouds and diffuse X-ray gas, but also observations such as radio halos in other galaxies and extraplanar emission-line gas in starburst galaxies. Although assuming this halo material comes from the disk does provide an explanation, it is not the only one possible: the material could be accreting onto the galaxy from the intergalactic medium, for example. One way of distinguishing between the possibilities is to measure the velocity of the extraplanar gas. Galactic fountain theory would predict that emission-line gas emerging from the disk would share in the, disk's rotation, while matter accreting onto the disk from the outside would not be rotating with the galaxy.

This type of investigation is difficult to carry out for the Milky Way because we are embedded in its disk. An edge-on external spiral galaxy would show extraplanar gas more clearly, and the kinematics of the gas would be relatively simple to measure and model. Realizing this, several groups have made observations of extraplanar gas in NGC 891, an edge-on galaxy thought to have a "remarkable similarity" to the Milky Way (van der Kruit, 1984). Rand et al. (1990) and Dettmar (1990) imaged NGC 891 in Hα and found diffuse emission outside the plane to $|z| > 4$ kpc (throughout this paper, we assume a distance to NGC 891 of 10 Mpc). Both studies also found "worms" or filaments of emission-line gas extending over 2 kpc from the disk. Similar structures in HI in the Milky Way have been interpreted as the cool outer surfaces of galactic chimneys. Keppel et al. (1991) took long-slit spectra perpendicular to the plane of NGC 891 and found $H\alpha$ emission at $|z| > 1.4$ kpc as well as coronation of this emission-line gas with the disk of the galaxy to within the accuracy of their measurements.

This study combines both higher resolution $H\alpha$ imaging of the NE side of the galaxy (the side seen to have the greatest amount of diffuse emission and filaments) and long-slit spectroscopy along two prominent filaments. Details of the observations and initial reduction are in section 2. The $H\alpha$ imaging revealed filaments and bubbles not found in any previous study, including a pair of bubbles on opposite sides of the plane (see Section 3). The imaging also allowed us to create a model of tile radial distribution of the diffuse emission (Section 4). This model, combined with the rotation curve of NGC 891 from Rupen (1991), is used to calculate the spectra of corotating gas. The comparison of these model results with our long-slit spectra shows sonic departures from coronation in the extraplanar gas. Further discussion and conclusions are in Section 5.

2. Observations

Both imaging and spectroscopy were done using the 2.4 m Hiltner Telescope at the Michigan-Dartmouth-MIT (MDM) observatory on Kitt Peak, Arizona. in both cases, we used the BRICC 135 mm camera (Luppino 1989) with a TI-4849 CCD (398 x 598 pixels).

2.1. Imaging

The imaging was carried out on 3 October 1991. With the f7.5 secondary on the telescope, the scale is 0.25" pixel^{-1}, giving a total field of view of 1.7'x 2.5'. At the assumed distance to NGC 891 of 10 Mpc, this corresponds to a linear size of 4.9 kpc x 7.3 kpc.

Four 900 s narrow band Hα images (using the KPNO filter set- the filter we used had a central wavelength of 6565 Å and a full-width-half-maximum of 73 Å) and one 900 s Cousins broadband R image were taken. All were centered on the apparent origin of the previously discovered 2 kpc filaments in the plane of NGC 891. The instrument was rotated so that the long axis of the chip was aligned with the plane of the galaxy.

The images were reduced using the standard IRAF packages and calibrated using standard stars observed by Massey et al. (1 988). The R band frame, scaled so that the stars in it were the same magnitude as those in the coadded Hα frame, was subtracted from that coadded frame to give Figure 1. The vertical line on the left side of the image is due to bleeding from a bright foreground star.

2.2. Spectroscopy

The spectroscopy was obtained 1 October 1991 under nonphotometric conditions using a 600 line/mm grism with a blaze wavelength of 5800 Å. The projected slit width was 1.68", giving a spatial scale of 0.728" pixel^{-1} and a dispersion scale of 2.27 Å pixel^{-1}. With the slit positioned along the long axis of the chip, the wavelength range covered was 5700-6900 Å.

Four 900 s spectra were takin each of three positions (see Figure 2): cuts A and B along two of the previously discovered filaments, and cut C perpendicular to the plane of the galaxy near the nucleus. Initial reduction of the spectra with IRAF produced one-dimensional spectra with 11 pixel wide apertures (8.01" or 0.388 kpc) for each cut. The first aperture in all cases was centered on the plane, with subsequent ones extending away from the plane in both directions. Far away from the plane where the emission was particularly weak but still evident, larger apertures were taken so an adequate signal-to-noise ratio could be obtained. The one-dimensional spectra were then analyzed using a modified version of the software package FIGARO (developed by K. Shortridge at AAO) to determine a central wavelength and full-width-half-maximum for the H α line, including the nearby [NII] and [SII] doublets when possible.

3. Results

The most prominent features of the continuum-subtracted Hα image of NGC 891 are the two bubbles emerging from opposite sides of the galaxy's plane near the outer edge of the diffuse emission region (Figure 1). The bubbles are approximately 2.1' (6.1 kpc) NE of the optical center of the galaxy. In addition to the two bubbles, diffuse emission outside of the plane of galaxy is quite apparent.

in determining the Hα luminosity of the bubbles, two problem s must be solved: defining the border of a region of interest, and compensating for the diffuse emission in the background. If the second problem can be solved, the first becomes less important because the net flux from areas around the region will be zero (it is straightforward to exclude areas of higher flux since they can be discriminated against). A third problem is determining what contribution the [NII] doublet near Hα make to the measured luminosity since the filter we used was broad enough to include those lines. Keppel et al. (1990) found Hα/[NII] ratios ranging from 0.9 to 2.5 at various heights and radii in NGC 891, so no definitive conversion from luminosity in the filter to Hα luminosity can be made. For the remainder of this paper, luminosities and fluxes will be the total for the filter, unless stated otherwise. In addition, no corrections are made for dust extinction since the dust content of these structures is not well known.

We used the PROS package in IRAF to try to obtain luminosities, since it permits one to draw polygons around regions and to choose background areas to be subtracted from these regions. In practice, we found that even the most careful choice of backgrounds still gave some significant variation (up to a magnitude in one case) in the luminosities of the regions under consideration, although it was less important for the brightest regions due to their high flux relative to the diffuse emission. Thus, when a range of magnitudes or luminosities is given, it represents the results from using a range of backgrounds.

Bubble A (in Figure 1, above the plane at the center of the image) is relatively symmetric. It has a diameter of 12" (580 pc); a filament emerges off of one edge. The background subtracted magnitude of the bubble is 17.4- 18.4 (depending on the background region selected), which corresponds to a luminosity of 1.2–3.0 x 10^{38} erg s^{-1}.

Bubble B (below the plane, directly underneath Bubble A) is much more irregular. It curves towards the far edge of the galaxy, and appears to have a hot spot at the edge furthest from the plane. It extends 10.3" (500 pc) from the large HII region (above Bubble B in Figure 1) that it apparently is associated with. The upper region of the bubble has a diameter of 6" (290 pc), below which it narrows, then widens again to a diameter of 8" (390 pc) at the HII region. It is difficult to determine if this bubble is a small blowout on top of a larger bubble or a single tilted and elongated structure.

This second bubble has a magnitude of 17.1-17,6, corresponding to a luminosity of 2.5- 4.0 $\times 10^{38}$ erg s^{-1}. The large HII region in the plane immediately beneath it has a magnitude of 16.6- 16.7 or a luminosity of 5.8- 6.3 $\times 10^{38}$ erg s^{-1}, approximately 1.5 to 2 times brighter than the bubble. If the smaller HII region to the left of the larger one is included, the magnitude increases to 16.1- 16.2, for a total luminosity of 9.1-10 $\times 10^{38}$ erg s^{-1}.

Other, more diffuse bubbles and bubble fragments also can be seen in Figure 1, though at lower levels of significance. To the left of Bubble B, a faint arc 23" long (1.1 kpc) appears to be part of an elongated, faded bubble. Straighter "worms" appear on both sides of the disk, with typical lengths of 10" (480 pc). These "worms" are reminiscent of the HI worms found by Heiles (1 984) in both shape and scale. There is a great deal of frothy small-scale structure in the emission-line gas within 1 kpc of the midplane, while farther away from the disk, little or no structure can be seen.

The diffuse emission-line gas found in previous studies (Rand et al. 1990, Dettmar 1 990) is clearly in evidence in our image. Towards the nucleus of the galaxy, diffuse emission is seen to the edges of the frame, however, it disappears rapidly and abruptly as one moves away from the nucleus. Figures 3a and b illustrate this more quantitatively with average pixel values taken parallel to the plane on both sides of the galaxy. Each point represents an average taken over an 11 x 11 pixel (2.8" x 2.8") box. The peaks correspond to either one of the two bubbles discussed above (rows 250- 300) or a strip across the top of the image (approximately row 450) where the bright star saturated and bled across the rows, 'J'here is a clear and precipitious decline in the values at the same radius where the disk 1111 regions become much less prominent. In section 4, we attempt to model the extraplanar structure responsible for this behavior.

The spectroscopy reveals systematic shifts in the 11 α line as one moves out from the plane of the galaxy along the 2 kpc filaments (Fig. 4a ant] b- points with error bars) and no such shifts--to within the error of our observations- perpendicular to the plane near the nucleus (Fig. 4c). The velocity difference is as large as 55 km s^{-1} along one of the filaments. Since in two of the three spectra we did not place the slit perpendicular to the plane of the galaxy, determining whether the diffuse gas is corotating or not requires a model of the emission measure ant] velocity field of the galaxy (indicated by the solid lines- see below for discussion).

4. Models

There were two stages to our modeling, each of which can be tested against the observational results discussed above. The first stage was to model the three-dimensional spatial distribution of the emission measure. This spatial model was projected against the plane of the sky in order to compare it to the measurements of the brightness of the diffuse emission observed above and below the plane of the galaxy. Once a good spatial model was found, the second stage was to use it and the rotation curve of the galaxy to predict the velocities of the extraplanar gas assuming that this gas is corotating with the galaxy. This velocity model can be compared to the spectroscopic observations to judge whether the systematic shifts seen are the result of significant non-corotating velocities above and below the plane.

For the first stage, we experimented with two simple three-dimensional spatial models to determine which more accurately describes the diffuse extraplanar emission. One model is a disk with constant emission measure per unit area as a function of radius (the emission measure does change as a function of height above the disk) and a sharp cutoff at the edge:

$$EM = \begin{cases} K & r \leq r_{galaxy} \\ 0 & r > r_{galaxy} \end{cases}$$

The other is a disk with an exponentially decaying emission measure with scale length r_s:

$$EM = Ke^{-r/r_s}.$$

In both cases we assumed an optically thin edge-on disk and projected the I11OC1C1 onto the plane of the sky to obtain the two-dimensional emission measure to compare with the photometry of the diffuse emission.

The two spatial models produced very different results for this first stage of modeling. The exponentially decaying emission measure model projected against the plane of the sky becomes a pelf'cr law declining as a function of distance from the center. The projected emission measure for the constant model as a function of radius is

$$EM_i(r) = EM_i(0)\sqrt{1 - \left(\frac{r}{r_{galaxy}}\right)^2}$$

While the constant model is much more similar to the observations than the exponential model (Figures 3 and 5), it is not a perfect match. The radius of the galaxy r_{galaxy} as determined from the observations varies with height above the disk, perhaps due to dust, although a good working value is 2.7' for this side (NE) of the galaxy. In addition, while the east side behaves much like the model predicts, the west side shows a much sharper dropoff than predicted. Some of these shortcomings may stem from the simplicity of the model, while others may arise from the limitations of the observations. Because the field of view of the CCD we used is so small compared to the angular size of NGC 891 , there was not enough sky in the image to perform an accurate sky subtraction]. in addition, the image may contain a gradient which was difficult to determine due to the lack of sky. Both of these problems are only at the few DN level, though; the constant model fits the . observations quite well considering its simplicity, so we used it in the second stage of the modeling.

The second stage of the modeling used the constant spatial model, but also required some information about the rotation curve of the galaxy. According 1,0 Rupen (1 991), the 111 rotation curve of NGC 891 is "roughly flat" at a velocity of 225 km s-' for radii between 1.2' and 5.5'. His data also show the rotation curve increasing linearly from O to 225 km S-' as the radius increases from 0 to 1.2'. With this model of the velocity field of the galaxy and the constant spatial model described above, we predicted the velocity centroids of the emission line gas along the three long-slit spectra. The spectrosc.epic observations and the velocity model's predictions are in Figures 4a- c.

One feature that is apparent on these plots is the high observed velocity (that is, low velocity relative to the center of the galaxy) of the central aperture (distance from plane =

O) in all three spectra, but this apparent deviation is expected. It is due to the aperture's sampling the dense, dusty disk rather than the transparent extraplanar gas. Since the central aperture samples the outer edge of the disk (which is not at the tangent point of the rotation curve at that radius), it obtains a smaller radial velocity relative to the center of the galaxy. The model thus should be applied only to the velocities of the apertures outside the plane.

A further question is whether dust could be distorting the velocities measured outside the plane. This can be estimated using Rupen's (1 991, 1992) 111 observations of NGC 891, assuming that HI traces the dust and the dust's properties arc similar to that in the Milky Way. Rupen finds that at the positions where wc have taken spectra, the column density of 111 in the plane is 10^{22} cm^{-2} and the vertical distribution of Hl is well-fit by a gaussian with $\sigma = 3''$. Using the 111-to-extinction conversions of Bohlin et al. (1 978), the extinction at $H\alpha$ for the centers of the apertures just outside the center of the plane ranges from 0.15 to 0.51 magnitudes, depending on the spectra] cut's angle with respect to the plane. The extinction is negligible for all apertures further from the plane, thus only the two apertures closest to the plane in each spectra cut arc possibly affected by dust extinction, and those arc affected only to a limited extent. Also, there is evidence that in the Milky Way, dust is more tightly confined to the disk than HI is. Diplas & Savage (1993) find that the dust scale height is less than 80% of that of HI (152 pc for dust versus 195 pc for HI), so extinction duc to dust may be even less than estimated above. Of course, the dust is not all smoothly distributed- -the dusty "tendrils" seen extending out of the disk of NGC 891 (Keppel et al. 1 990) arc not accounted for in this treatment— but there is no systematic way of treating these non-uniformities in the dust distribution. The large FWHM's found in our spectra (discussed below) imply that wc arc seeing all the way through the galaxy, however.

The spectra. taken along filaments snow significant deviations from the model velocities, while the spectrum taken near the nucleus agrees well with the model predictions. Spectrum

A- taken through a filament on the east side of the galaxy—shows slightly more than 1 σ deviations on the filament side, but 30–50 km/s deviations on the west side. The diffuse gas on the west side is rot sting *faster* than corot ation. Spectrum ~~–taken through a filament on the west side of the galaxy---appears to have velocities systematically lower than coronation. The trend across the galaxy is similar to the model, but is 20--30 km/s slower than coronation. In genera], the presence or absence of a filament seems to make little difference in the measured velocity structure of the extra.planar gas.

In addition to modeling the line centers, wc modeled the full-width-half-maximum (FWHM) of an emission line in the coronation model for comparison with the observed values. Using DRAWSPEC,[1] we fit theoretical lines for each aperture with gaussians to obtain FWH M's, then found the mean for each cut, weighting by the errors of the observed aperture FWHM's. We subtracted the instrumental FWH M from the observed aperture FWHM's, and found a mean value for each cut, also weighting by the observed errors (Table 1). There is no observed FWHM for cut C because the aperture values cluster around the instrumental FWH M—it is indistinguishable from an unresolved line.

The theoretical FWHM for spectrum A is within 1 σ of the observed one, but for spectrum B it is over 2 σ below it. In both cases, the observed FWHM is greater than the theoretical one. Since each aperture has an internal dispersion on the order of 6 km s--' (smaller than the observational error), this increase in the FWHM is not simply due to dispersion within each aperture, but rather it must reflect overall behavior within the ex t rap] an ar gas. It is unclear whether this increase is due to random or ordered velocities in the filaments, or both. If it is due to turbulence alone, the turbulent velocities for cut B are as high as 100 km S–l.

[1] DRAWSPEC is a spectral analysis program developed by 11. Liszt at the National Radio A stronomy Observatories.

5. Discussion and Conclusions

The properties of superbubbles in NGC 891 can be compared to those in our galaxy, which is similar in type and mass to NGC 891, and the nearby spirals M31 and M33. Superbubbles in our Galaxy (like the Local Superbubble) have radii on the order of 100-1000 pc and kinetic energies of approximately 1050 – 10^{54} ergs (McCray & Kafatos 1987 and references therein). HI holes in M31 (Brinks & Bajaja 1986) and M33 (Deul & den Hartog 1990) are very similar, ranging in size from the resolving power of the survey up to 1000 pc and in energy 10^{49} – 1054 ergs. For both galaxies, the mean kinetic energy per hole is 10^{51} ergs and the mean age is approximately 5 --- 10 x 106 yr, giving an average luminosity of 1 --3 $\times 10^{36}$ erg s^{-1}.

The two most prominent bubbles that we found had diameters of 500-600 pc and filter luminosities of roughly 1038 erg s-1. This size is similar to the HI holes found in the Milky Way, M31 , and M33, but the luminosit - even if corrected for [NII] emission- -is more than an order of magnitude greater than the average luminosity of the HI holes. This latter difference may be due to a rapid loss of energy in the early stages of superbubble evolution; it is unlikely that the luminosity remains constant over the entire lifetime of a bubble. Some of the fainter bubbles and filaments in NGC 891 extend up to 1 kpc from midplane (Rand et al. 1990 found filaments more than 2 kpc long), but most of the faint structure is on the scale of 200-500 pc. Mac Low, McCray, & Norman (1989) suggested that the lower halo of the Milky Way might be "a froth of merged superbubbles", and the lower halo of the NE side of NGC 891 appears to be similar to this picture. Many faint arcs and filaments are seen within a kpc of the plane. No obviously merging bubbles are apparent, but this may be due solely to rapid fading of the emission-line luminosity of the bubbles.

Theories of superbubble formation and evolution suggest that bubbles will elongate in the z direction as they expand, becoming chimney-like as they break out (Mac Low, McCray, and Norman 1989, Norman & Ikeuchi 1989, Tomisaka 1991). The bubbles and bubble fragments seen in the Hα image of NGC 891 provide neither strong support nor contradiction to this view. While no obvious "chimneys" are seen, most of the structures visible are more extended in the z direction than in the radial 'direction. In addition, the emission appears enhanced at the top of both of the complete bubbles, perhaps indicating that they are approaching breakout.

Coronation of the extraplanar ionized gas would imply that this gas is emerging from the disk, rather than accreting from the halo, but the observed departures from coronation can also be accomodated if the gas comes from the disk. The presence of Hα filaments and bubbles implies that warm disk gas is escaping from the plane towards the halo. The departures from corotation may imply is that the violence of the processes sending disk gas into the halo produces substantial turbulence in the extraplanar medium. This view is supported by the large FWHM's of the Hα line along the two filament cuts. Also, the expansion and breakout of the superbubbles likely imparts some significant velocity to the gas involved. in addition, the high velocity HI cloud study of Kaelble, de Boer, & Grewing (1 985) shows that in the Milky Way, these clouds fall below coronation by approximately 150 km s^{-1} and that this behavior is consistent with the predictions of galactic fountain theory, While warm gas n-Loving from the disk to the halo should be closer to coronation than would be cold gas falling back into the disk from the halo, our departures from coronation of under 40 km s^{-1} are modest compared to the nigh velocity clouds' departures.

The spatial and velocity structure of the extraplanar emission-line gas in NGC 891 is clearly very complicated, and this study has produced intriguing, if not unambiguous results. More precise spectroscopy of the 2 kpc filaments and the diffuse gas would help determine the extent of the gas's departure from coronation, and spectroscopy to larger $|z|$ would help determine whether the departures seen are from turbulent or systematic motions in the gas. Further study of NGC 891 should help us understand the dynamic nature of the interstellar medium in our own galaxy much more clearly.

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Spectrum	Measured FWHM	Predicted FWHM
A	108 ± 10 km/s	97.6 km/s
B	113 ± 16 kin/s	74.8 km/s
C	n/a	n/a

Table 1: Measured and predicted (corotation model) full-widths-h alf-maximum

Fig. 1---- Colltillullllll-subtracted $H\alpha$ image of the NE side of NGC 891. The upper image has been convolved with a Gaussian with FWHM=1 .25"; the lower image is a gradient-shaded version of the upper image. Gradient shading emphasizes differences between adjoining pixels. In both images, north is to the lower right, east is to the upper right.

Fig. 2----- $H\alpha$ map of NGC 891 courtesy of R. Rand, marked to show the spectra taken in this study. North is up, east is to the left.

Fig. 3.- Average pixel values parallel to the plane on the east (a) and west (b) sides versus radial distance from the center of the galaxy. In 3a, the crosses represent values taken 17" (0.82 kpc) above the plane and stars represent values taken 25" (1.2 kpc) above the plane. In 3b, the crosses represent values taken 15" [0.73 kpc) above the plane and the stars represent values taken 31" (1.5 kpc) above the plane.

Fig. 4.- Observed line centers of $H\alpha$ along the three spectra] cuts marked in Figure 2 (points with error bars) and theoretical prediction of the velocity structure of an optically thin corotating halo (solid line). Figures 4a- c represent cuts A- C, respectively. Negative distances are east of the plane, posit, ve distances are west.

Fig. 5.- Projected emission measure for an optically thin halo as a function of radial distance from the center of the galaxy for the truncated (a) and exponential (b) models.